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NASA RESEARCH ON MATERIALS APPLICABLE TO SUPERSONIC TRANSPORTS

by Herbert F. Hardrath and George J. Heimerl

Langley Research Center
Langley Station, Hampton, Va.

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NASA RESEARCH ON MATERIALS APPLICABLE TO SUPERSONIC TRANSPORTS[1]

By Herbert F. Hardrath and George J. Heimerl

SUMMARY

The National Aeronautics and Space Administration has conducted tests to determine the mechanical properties of materials suitable for use in a supersonic transport over the temperature range of interest and after prolonged exposure to temperature. On the basis of studies on fatigue behavior, rate of fatigue crack propagation, residual static strength, and resistance to deterioration of properties due to prolonged exposure to temperature, no serious materials problems are anticipated. However, stress corrosion is found to be a potentially serious problem in titanium alloys in a hot salt environment and in stainless steels in an ambient environment. The Ti-8Al-1Mo-1V alloy is found to be generally superior to other contending materials in all respects studied except for salt stress corrosion in which respect it was poorer than all others. Further research is recommended on stress corrosion; on the combined effects of fatigue, thermal exposure, and creep; and on the development of structural configurations and fabrication procedures suitable for the supersonic transport.

INTRODUCTION

The design of a successful supersonic-transport structure is in large part contingent upon the proper selection of material and in the use of proper allowable stress levels. Current airplanes may utilize established materials at stress levels that experience has proven will produce efficient and reliable structures, but such background information does not exist for materials of interest to the designers of a supersonic transport.

This paper presents some of the results of several studies into the behavior of various materials that were candidates for use in the structure of a supersonic transport at the time the studies began. The results of earlier studies for "screening" purposes are not included because the data and conclusions drawn from them have been published in reference 1. Most of the work described herein was done at the Langley Research Center, but some information from contracted studies (refs. 2 and 3) and from the Lewis Research Center is also included.

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*This paper was originally presented at the NASA Conference on Supersonic-Transport Feasibility Studies and Supporting Research - Langley Research Center, Hampton, Va. - September 17-19, 1963.

In order to exaggerate the temperature effect, the earlier screening studies treated a wide variety of sheet materials subjected to quick tests at temperatures higher than those that will be encountered in the transport. The present paper deals with a few selected materials tested in more nearly realistic ways at realistic temperatures and includes the effects of long-time exposures. It is believed that these results will be helpful in making final selections of materials and in choosing the allowable stress levels to be used in design. This discussion is limited to materials suitable for use in the skin of a vehicle capable of traveling at a Mach number of 3.

SYMBOLS

K_T	stress concentration factor
N	number of cycles to failure
N_O	number of cycles to failure of unexposed specimens
R	ratio of minimum stress to maximum stress
S	stress
S_m	mean stress
S_N	strength of a notched specimen
S_{TU}	tensile ultimate strength
S_{1g}	stress for 1 g loading at take-off gross weight

Abbreviations:

A	aged
CR	cold rolled
CRT	cold rolled and tempered
DA	double aged
El	elongation in 2-inch gage length
GAG	ground-air-ground
HT	heat treated
MA	mill annealed
TA	triplex annealed

STATEMENT OF PROBLEMS

In order to focus attention on the specific questions to be discussed, it is of interest to review the operating environment for major portions of the structure. Figure 1 represents a time history of stress for typical flight at a given station on the wing of the airplane. Obviously, this time history will change significantly, depending upon the specific airplane configuration, the station within the airplane, the particular flight, dynamic response characteristics, and so forth. However, the general features will usually be similar to those shown. The stress values are normalized with respect to the nominal stress present for level undisturbed flight at takeoff gross weight. (The time axis in fig. 1 is not to scale.)

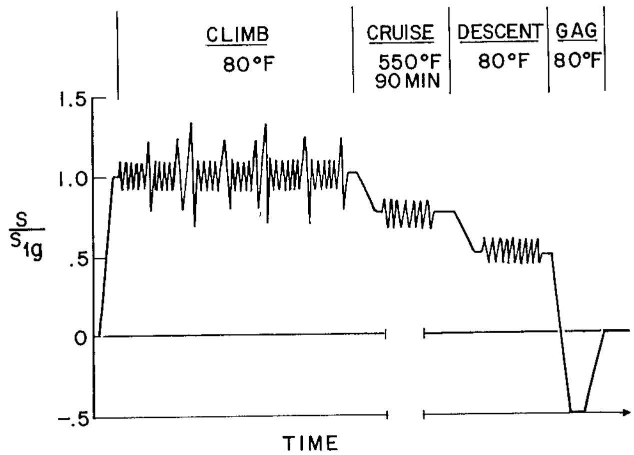

Figure 1. - Schedule of loads and temperatures for supersonic transport flight.

The features of interest to the structural designer are as follows:

(1) Most of the significant stress cycles occur during the climb portion of the flight while the airplane is at ambient temperature.

(2) Few dynamic stress cycles are encountered during cruise because gust activity is reduced at high altitudes.

(3) The exposure to elevated temperatures up to about 550° F may be as long as 90 minutes per flight.

(4) The change in temperature can produce thermal stresses of significant magnitude, depending on detail designs. These stresses are not shown in figure 1.

(5) Dynamic loads encountered during descent are less severe because the airplane has lost substantial weight because of the burning of the fuel.

(6) At stations outboard of the landing gear, a rather significant ground-air-ground cycle is introduced.

(7) With the exception of the length of exposure to elevated temperatures, the fatigue damage accrued during a given flight is, to a first approximation, independent of flight length.

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Some of the engineering questions that must be answered to provide a structure capable of surviving the loadings shown for useful lives of the order of 36,000 hours are as follows: First of all, the basic material properties must be established over the temperature range of interest. In the NASA studies, the notch and tensile strengths, basic fatigue behavior, rates of fatigue crack propagation, and residual static strength of sheets containing cracks were obtained. Of the various studies made of creep properties, it appears that overall creep will not be a significant problem if the structure is built of any of the leading titanium alloys, stainless steels, or superalloys. Having established these properties over the temperature range of interest, one must know how some of these properties might be affected by the prolonged exposure to elevated temperatures. The Langley Research Center has studied notch and tensile strengths, fatigue behavior, the rather perplexing salt stress corrosion, and strain-rate sensitivity. Inasmuch as the last of these properties was studied to only a limited extent with no significant effects found, it is not discussed further. Some work has been started on methods of welding the materials of interest and on studying the effects of fabrication procedures on the strength of structural components.

RESULTS OF RESEARCH IN INDIVIDUAL PROBLEM AREAS

In the following sections, problem areas are discussed with sample data presented to indicate the conclusions reached in each investigation. Generally, no insurmountable problems have been discovered and the Ti-8Al-1Mo-1V alloy appears to be one of the best available on the basis of the results given herein. Salt stress corrosion has been found to be one of the areas of concern and one on which additional study is recommended. Most of the various investigations were carried out on each of the following sheet materials:

	Condition
Titanium alloys:	
Ti-4Al-3Mo-1V	Aged
Ti-6Al-4V	Annealed
Ti-8Al-1Mo-1V	Mill annealed
Ti-8Al-1Mo-1V	Triplex annealed
Stainless steels:	
AM 350	Double aged
AM 350	Cold rolled (20%) and tempered
PH15-7Mo	TH 1050
PH14-8Mo	SRH 950
AISI 301	Cold rolled (50%)
AM 367	Cold rolled (20%) and tempered
Superalloy:	
René 41	B

Only a few tests have been conducted on the superalloy René 41, which may be useful in the construction of leading edges and nacelle structures.

Fatigue Behavior

Most of the study of fatigue behavior of materials of interest in the design of a supersonic transport was devoted to Ti-8Al-1Mo-1V alloy and to AM 350 stainless steel. The titanium alloy was studied in the mill-annealed and in the triplex-annealed conditions and the AM 350, in the cold-rolled-and-tempered condition. A major part of this research was conducted under NASA contract at Battelle Memorial Institute (ref. 2) and at Chance Vought Corporation (ref. 3).

A summary of some of the data on the titanium alloy is shown in figure 2. The bar graphs indicate the fatigue strength at a life of about a million cycles for each of several configurations tested at room temperature (80° F), 550° F, and 800° F. All tests were conducted on sheet specimens subjected to axial loads producing a mean stress of 25 ksi.

The fatigue strength of unnotched specimens was not adversely affected by the elevated temperatures; in fact, a slight increase in strength was noted. The mill-annealed material behaved as well as the triplex-annealed material in unnotched specimens. Fusion welding of the mill-annealed material produced only a moderate reduction in strength. A specimen having an unloaded square of material spot-welded to one face had a fatigue strength about the same as that for a specimen with an open hole with a stress concentration factor of 2.5. A spot-welded double butt-strap joint had fatigue properties not too different from those of edge-notched specimens with a theoretical stress concentration factor of 4. This latter configuration is identical to the configuration Langley has come to regard as representative of the overall quality of construction achieved in current aluminum-alloy structures. The effect of temperature is minor in all cases where it was studied as a parameter.

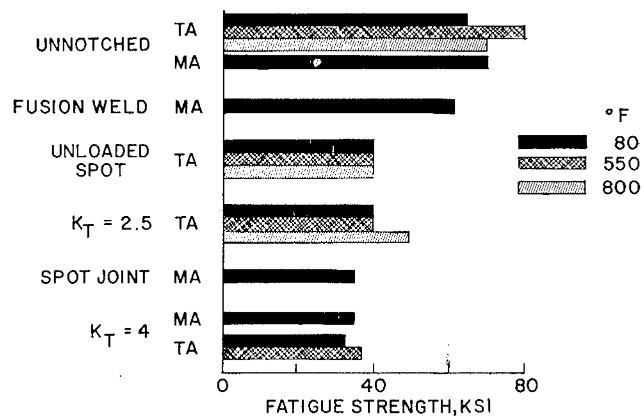

Figure 2. - Fatigue strength at $N = 10^6$ cycles of Ti-8Al-1Mo-1V. $S_m = 25$ ksi.

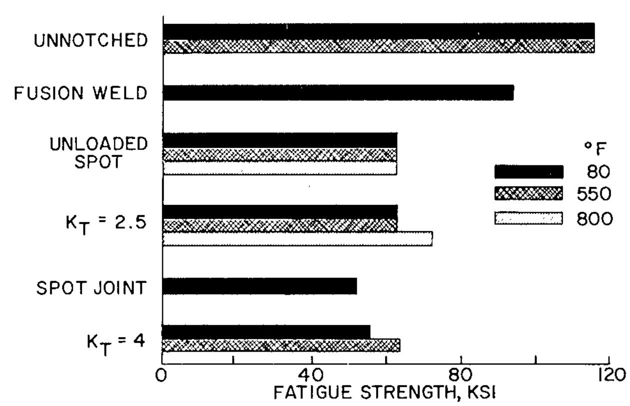

Figure 3. - Fatigue strength at $N = 10^6$ cycles of AM 350 (CRT). $S_m = 40$ ksi.

The same general comments apply to results of tests on AM 350 stainless steel which are presented in figure 3. The mean stress for this material was 40 ksi.

These limited results do not, of course, provide all the information needed to design a structure from a fatigue point of view. However, they do indicate that notch sensitivities are reasonable and that welds and spot-welds produce strength reductions not too different from those of stress raisers representative for current structures. Obviously, considerable testing will be required to prove the adequacy of specific design details.

Information is still needed on the possible interaction of creep and fatigue, especially around fasteners and other points of stress.concentration.

Ti, SS, AL

Fatigue Crack Propagation

The rate of fatigue crack propagation is a most significant consideration in assessing the fail-safe characteristics of a structure. Figure 4 presents a sample of data obtained in axial-load fatigue tests of 8-inch-wide sheet specimens tested at $R = 0$ (zero to tension loading). The rate of crack propagation is a reasonably straight-line function of crack length when both are plotted on a log scale. The results presented are for room-temperature tests with a mean stress of 25 ksi for titanium alloys and 40 ksi for steels. The most desirable material would be the one having the lowest rate of crack propagation. Of the titanium alloys, the Ti-8Al-1Mo-1V alloy in the triplex-annealed condition is superior. Two stainless steels, AM 350 (CRT) and AISI 301, appear superior to the Ti-8Al-1Mo-1V alloy, but the rate of propagation in both materials increases by a large factor at elevated temperatures.

For reference, the rates of propagation for two aluminum alloys, 2024-T3 and 7075-T6, are also plotted in figure 4. The data shown are for a mean stress of 15 ksi. The steeper aluminum-alloy curves at these stress levels indicate a faster increase in rate of crack propagation as a function of crack length. The 7075-T6 material also experiences crack growth rates higher than those for the other materials shown.

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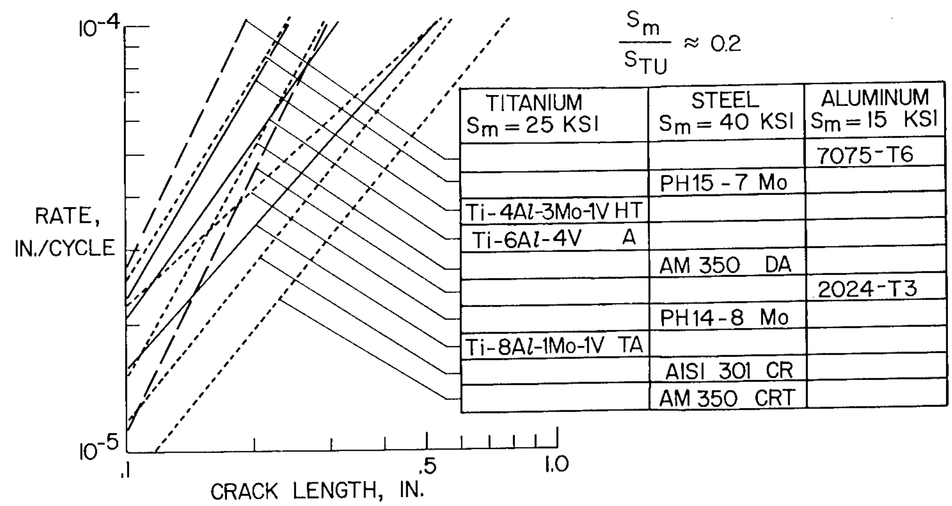

Figure 4. - Fatigue crack propagation in centrally notched titanium, steel, and aluminum sheet specimens. 8 inch width; $R = 0$; 80° F.

The effect of temperature was studied at -110° F and at 550° F. The results are not presented herein; however, this preliminary study indicates that rates of fatigue crack propagation at the stress levels considered are not too different from the behavior of current aluminum alloys at a corresponding stress level. The effects of temperature are moderate except for AISI 301 and AM 350 (CRT), which experienced a marked increase in rate of crack propagation at 550° F. The Ti-8Al-1Mo-1V alloy stressed at 25 ksi appears to be the best choice from among the materials tested.

Residual Static Strength

Another important consideration with regard to fail-safe characteristics is the residual static strength of a part containing a fatigue crack or other damage. Langley conducted static tests on the same set of specimens used to study rates of fatigue crack propagation (ref. 4). A sample of the results is shown in figure 5. The solid bar graphs show the residual strength of specimens containing 1-inch cracks as compared with the original static tensile strength of the material. The stresses are divided by density to compare structural efficiencies. The data were obtained for nine materials at -110° F, 70° F, and 550° F.

In general, the strength of these materials exhibited moderate sensitivity to cracks. Exceptions are AM 350 (DA) and PH15-7Mo, both of which had low strength and failed by shattering at the lowest temperature, and AISI 301, which deteriorated seriously at elevated temperature. The titanium alloys are generally superior on a strength-density basis, Ti-8Al-1Mo-1V in the triplex-annealed condition being the overall leader. The triplex-anneal process improved the residual static strength of this latter alloy at room and subzero temperatures. In several materials tested at elevated temperatures, cracks produced little or

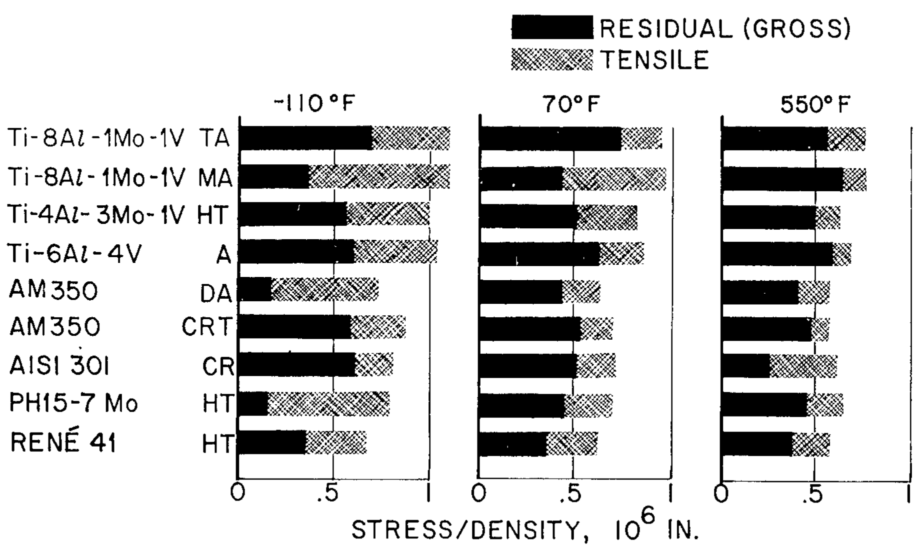

Figure 5. - Residual and tensile strengths of specimens. 1-inch crack in 8-inch specimen.

no reduction in residual static strength beyond that of reducing the cross-sectional area. The superalloy René 41 did not compare favorably in these tests. It is, of course, affected very little by temperature.

Although the data presented in figure 5 are for 1-inch cracks only, the general ranking of materials would be quite similar if strengths for other crack lengths had been compared. In most cases the reduction in static strength caused by cracks is moderate and, in general, is considerably less than that for current aluminum alloys. Several materials experience no loss of static strength except that produced by loss of area. Again, triplex-annealed Ti-8Al-1Mo-1V is the best overall choice of the materials evaluated.

Notch and Tensile Strength After Exposure to Temperature

The Langley Research Center is conducting a study of the effects of prolonged exposure to elevated temperatures on static tensile and notch strength properties. Specimens are exposed without stress at 550° F for various periods of time and then tested at room temperature and at -110° F. The notched specimens were 1 inch wide and contained 60° V-notches with root radii <0.001 inch (ASTM type, ref. 5). Table I presents a summary of the results obtained to date. Exposure times up to 14,000 hours have shown no significant effect on static tensile or on notch strengths. In a few cases, elongations in 2 inches have shown rather large percentage changes, but most of the materials in question have rather low elongations (4 to 8 percent) initially, so the absolute changes are not much greater than the accuracy of measurement.

TABLE I.- EFFECT OF EXPOSURE AT 550° F

Material	Condition	Exposure time, hr	Test temperature, $^\circ$F	Percent change		
				S_{TU}	S_N	El
Titanium alloys						
Ti-6Al-4V	A	14×10^3	-110 80	0 0	0 0	0 15
Ti-8Al-1Mo-1V	A	10	-110 80	0 0	0 0	--- -10
Ti-4Al-3Mo-1V	HT	7	-110 80	-- 0	0 0	10 25
Stainless steels						
PH15-7Mo	HT	7×10^3	-110 80	-- 0	-5 5	--- 25
AM 350	CRT	7	-110 80	0 0	0 0	10 5
AISI 301	CR	4	-110 80	10 10	5 5	0 -50

Some of the studies at the Lewis Research Center indicated stability problems with the two precipitation hardened stainless steels, PH13-8Mo and PH14-8Mo, and with AM 367 when exposed without stress at 650°. Special heat treatments of AM 367 have improved the stability characteristics but at the expense of a serious decrease in corrosion resistance.

Unstressed exposure to elevated temperatures for as long as 14,000 hours at 550° F produced no significant effect on static strength properties at 80° F and -110° F. Consequently, the materials studied at Langley appear to be reasonably stable for the exposures obtained at the present time.

Fatigue Behavior After Exposure to Temperature

In another study, fatigue test specimens are being exposed to 550° F for prolonged times without stress. Although eight materials are being tested, only the results for Ti-8Al-1Mo-1V in the mill-annealed condition are presented. (See fig. 6.) Four configurations of specimens were tested: unnotched, edge-notched ($K_T = 4$), fusion-welded, and a double butt-strap spot-welded joint. Complete S-N curves were derived from axial-load tests of unexposed specimens, but exposed specimens were tested at a single stress level chosen to produce failure in approximately 10^5 cycles. The mean stress in all cases was 25 ksi and all tests were at room temperature. The data presented are normalized with respect to the life of unexposed specimens and are plotted against exposure time in hours. Each point is the geometric mean of five test results. These data for Ti-8Al-1Mo-1V display almost the extreme variations noted in this series of tests which included seven other materials. A factor of about 2 or less on fatigue life is noted at each data point except the one for unnotched specimens exposed for 9,000 hours, which had a life 10 times as long as the original. This highest point is probably not valid because two of the tests produced lives much more nearly equal to the original life; thus, this point may be associated with the small statistical sample used. Data at exposure times in excess of 9,000 hours are not presently available and information for higher exposure times must await further investigation.

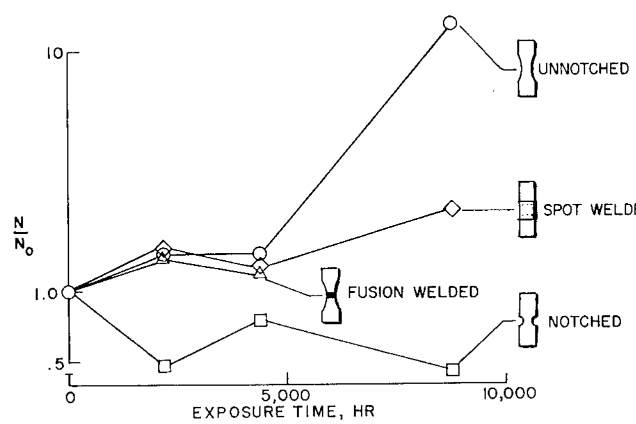

Figure 6. - Fatigue life after exposure to 550° F of Ti-8Al-1Mo-1V (MA).

The data available at this date show no cause for alarm over deterioration of fatigue properties with exposure. This general conclusion is supported by supplementary information obtained at Battelle (ref. 2) where notched specimens of AM 350 were tested in fatigue after exposure to 550° F under 40 ksi stress for 3,000 hours with no significant effect of this exposure on fatigue behavior.

Ti, SS

Salt Stress Corrosion

The final investigation that is to be discussed in detail is a study of salt stress corrosion at elevated temperature, a recognized problem area for titanium alloys. Figure 7 presents a summary of results (ref. 6) of salt-stress-corrosion studies conducted at Langley. Strips of sheet about 1/4 inch wide and 4 inches long were bent through a specified angle near each end so that when two such strips were spot-welded at the ends, as indicated by the small sketch, the center portions were subjected to constant bending stresses of either 50 ksi or 100 ksi. The specimens were dipped in concentrated salt solutions to form a substantial coating over the entire specimen. The coated specimens were stored in ovens at 550° F for various times. Upon removal from the oven, the specimens were cleaned and subjected to axial compression loads as indicated in the sketch. The reduction or shortening in the overall length of the specimen prior to failure of one of the legs was noted. This value is normalized relative to the value obtained in unexposed specimens and plotted against the exposure time in hours. If severe stress-corrosion cracking occurs, the shortening at fracture is reduced and the relative shortening may approach zero. Metallographic examinations have shown that the depth and number of stress-corrosion cracks in the specimens correlates well with the relative shortening parameter plotted in figure 7. The Ti-4Al-3Mo-1V alloy is virtually unaffected by salt stress corrosion but Ti-8Al-1Mo-1V (MA) is affected very severely in only 2,000 hours of exposure and Ti-6Al-4V, in 4,000 hours. No specimens have failed in the furnace in as many as 7,000 hours.

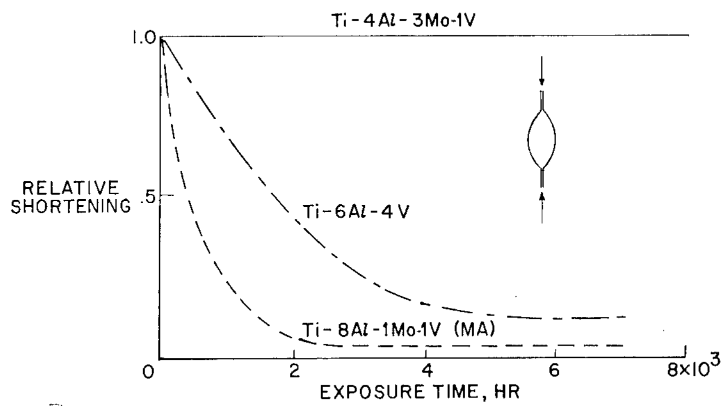

Figure 7. - Results of salt-stress-corrosion studies of specimens at 550° F.

The same tests have been conducted on the stainless steels with no effect noted when the compression test was conducted immediately upon removal from the oven. However, several specimens of AM 350 (DA) have failed in about 2 months after removal from the oven. Also, one specimen of AM 350 (DA) failed after several months exposure to the Langley outdoor atmosphere without salt and without artificial heat.

It is difficult to assess the importance of the salt-stress-corrosion problem. Certainly the test condition is severe but not so severe as to suggest that no problem exists. If moisture, and thus soluble contaminants, can reach the inside of the structure or lodge in crevices on the outside, salts will tend to collect over a period of time in service. Tests elsewhere in fast-moving air have indicated that the attack is less severe under these circumstances. However, the insides of structures will not have such ventilation. It was disappointing to find Ti-8Al-1Mo-1V most susceptible to this attack when this material appears to be one of the most suitable of the materials based on other

considerations. The problem deserves more study with emphasis on a more realistic representation of conditions to be encountered in service. Some information on the combined effects of corrosion and fatigue is desirable.

The problem of stress corrosion may be quite serious for steels in view of the fact that failures occurred without salt or heat.

The final solution to the stress-corrosion problem may require some form of corrosion inhibitor and probably very careful inspection.

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

Recent investigations on the properties of titanium and stainless-steel sheet materials suitable for a supersonic transport indicate that:

1. The fatigue problem appears not to be a formidable barrier at the stress levels considered.

2. Fail-safe considerations involving rates of fatigue crack propagation and residual static strength appear more promising for the better titanium and stainless-steel materials tested than is true for current aluminum alloys.

3. Prolonged exposure to 550° F has not been found to degrade static and fatigue properties significantly, at least in the first 10,000 to 14,000 hours.

4. Stress corrosion may be a problem with titanium alloys in dry salt at elevated temperatures and in some of the stainless steels at normal temperatures.

5. Of the contending materials, Ti-8Al-1Mo-1V alloy appears superior from all viewpoints considered except stress corrosion in salt.

6. Further study is recommended to evaluate the combined effects of dynamic loadings, thermal exposure, and creep.

7. Further study is also needed to assess the severity of the salt stress corrosion for titanium alloys at elevated temperatures for supersonic transport applications.

8. Studies are needed to develop practical, efficient, and reliable structures for supersonic transports built of titanium alloy.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., September 18, 1963.

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"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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